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A review of room temperature linear reciprocating magnetic refrigerators

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ABSTRACT

Various AMR refrigerators prototypes have been developed with a view to implementing magnetic refrigeration (MR) at room temperature in a short time. This article describes the working mode of the two basic categories into which these can be divided (reciprocating and rotary) and compares them to show the advantages and disadvantages offered. A review of the latest and most significant alternative linear prototypes is carried out, providing design concepts and performance characteristics. Such characteristics include the operating frequency, magnet field type and field strength, regenerator materials and geometry, and maximum temperature span and cooling capacity. Also included is a study carried out by the authors focused on the prototyping of an MR system aimed at avoiding the shortcomings of other prototypes manufactured to date.

Contents

1. Introduction

Room temperature MR is an environmentally friendly cooling technology with zero ozone depletion potential and zero global warming potential. It is an interesting alternative to conventional refrigeration based on vapour compression with working fluids that

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Nomenclature

Acronyms

MR	magnetic refrigeration
MCE	magneto-caloric effect
AMR	active magnetic regenerator
COP	coefficient of performance
HTF	heat transfer fluid
CHEX	cold heat exchanger
HHEX	hot heat exchanger

Symbols

η	fluid flow rate
B	magnetic induction
η	efficiency
F	force
Q	heat transfer
T	temperature
t	time
l	displacement
w	work

Subscripts

h	heat
c	cold
d.sys	displacement system
heat-pump	heat transfer circuit

do cause ozone depletion and global warming [1,2]. Scientists and engineers around the world are currently researching and developing MR near room temperature for its possible implementation in commercial and industrial applications for air conditioning and refrigeration. MR was first applied in low temperature physics for liquefaction of hydrogen and helium (cryogenic). The method which usually operates with paramagnetic salts to obtain sub Kelvin temperatures is outside of the scope of this review.

Dieckmann et al. [3] commented that a lot of recent and ongoing research has focused on improving the performance of MR systems applied at room temperature range to achieve similar or greater efficiencies at similar or better cost efficiencies to that of vapour compression equipment. Among the attributes of MR systems are their efficiency and their low power consumption, as well as being compact and virtually silent.

MR is based on the magnetocaloric effect (MCE), which consists in the entropy change of a magnetic material when adiabatically demagnetized, resulting in a heat absorption of magnetic material. This effect was discovered by Warburg in 1881 with iron metal [4]. MCE is a practically reversible thermodynamic process. However, it is not possible to directly use the MCE for cooling. Specialised cooling cycles are required for the MR to be used in conventional cooling [5,6]. In 1976, Brown was the first to use MR at room temperature with a refrigerator operating according to the Ericsson cycle [7]. Subsequently, the concept of active magnetic regenerator (AMR) was submitted by Steyert [8] and developed by Barclay [9,10]. Then, Chen et al. determined that, with the exception of the Carnot cycle, AMR is the most efficient refrigeration cycle for MR at room temperature [11]. Most room temperature MR prototypes up to present day operate according to the AMR cycle. Yet, the geometry, arrangement and the shape wherein the AMR interacts with the magnet and the heat transfer subsystems can vary widely. With regard to its displacement method, the prototypes can be classified into two basic categories: reciprocating and rotary. Scarpa et al. [12] have carried out an exhaustive classification proposal for MR prototypes. Each of the configurations mentioned has its advantages and disadvantages, later analysed in this article. The drawbacks posed by reciprocating devices have motivated researchers to opt mostly for rotary devices over reciprocating ones.

This article carries out a review of the most relevant reciprocating linear prototypes. It does not seek to fulfill a comprehensive review of alternative linear prototypes, but rather considers the most recent and relevant ones for analysing and summarising the different possibilities of configuration, geometry, magnetocaloric materials and operation, thereby providing researchers with possible improvement ideas in design and operation for prospective developments of future linear reciprocating magnetic refrigerators.

The end of the article provides a summary of the research which is being carried out by the authors focused on the development and prototyping of a reciprocating system of the AMR in order to eliminate the disadvantages that these present for its implementation in commercial applications.

2. AMR refrigeration cycle

In 1982, Barclay [9] patented a new concept of the AMR. With it, the magnetic material not only serves as a refrigerant for providing temperature change as a result of magnetisation or demagnetisation, but also as a regenerator for the flow of heat transfer. In essence, a temperature gradient is established throughout the AMR and a fluid is used to transfer heat from the cold end to hot end. This subtle but nonetheless essential idea has produced a new magnetic cycle different to Carnot, Ericsson, Brayton, or Stirling ones.

Due to the nature of the coolant (solid), the AMR cycle includes a heat transfer fluid (HTF) that links the refrigerant to the cold heat exchanger (CHEX) and hot heat exchanger (HHEX). This requires correct synchronisation between the change of magnetic field and the HTF flow. The magnetocaloric regenerator material is immersed in the HTF and, by means of pistons or pumps, the HTF can move through the regenerator. The AMR cycle cannot be illustrated through a temperature-entropy diagram. Each portion of the regenerator performs an individual thermodynamic cycle, linked to one other by the HTF.

The working principle of an AMR refrigerator and its basic components, by way of example, is illustrated in Figs.1 and 2. The refrigerator consists of the following parts:

- a device responsible for creating the magnetic field,
- a regenerator with magnetocaloric material,
- CHEX and HHEX, and
- a device providing the flow of HTF through the active regenerator.

The AMR cycle is based on four processes: magnetisation, demagnetisation and two processes where the intensity of applied magnetic field remains constant. These processes are depicted in Fig. 1. With reference to Fig. 1, assume that the regenerator is at an initial stationary state where the fluid and magnetocaloric material have the same temperature.

(a) *Magnetisation Process*. The magnetic field is applied to the magnetic material. Magnetic material temperature increases due to the MCE, while also increasing the temperature of the HTF in the AMR due to heat transfer.

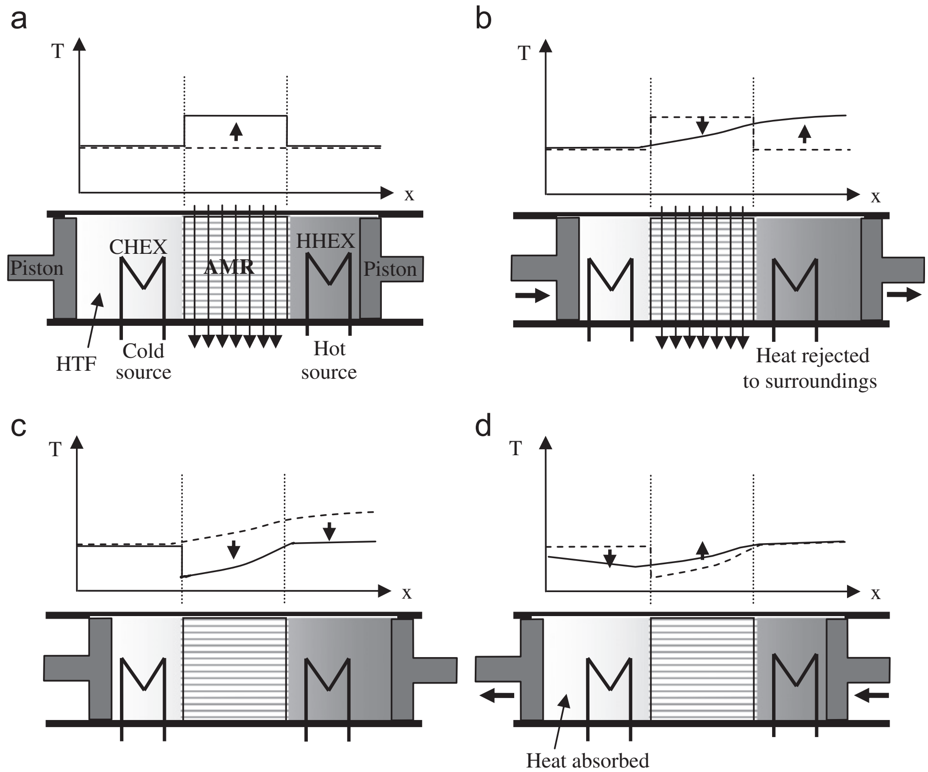

Fig. 1. Schematic illustration of a magnetic refrigerator cycle based on the AMR cycle. (a) Magnetisation, (b) Fluid flow, (c) Desmagnetisation, (d) Fluid flow.

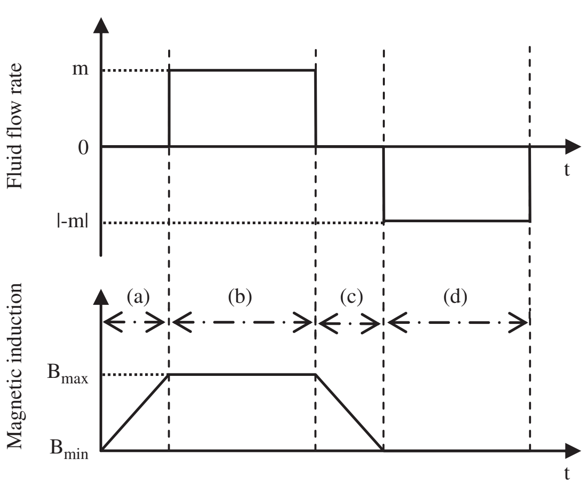

Fig. 2. Example of a time diagram AMR cycle.

(b) *AMR cooling process to a constant applied magnetic field*. This process is performed as a result of the AMR's HTF displacement with fluid from CHEX. The fluid absorbs heat from the regenerator and releases it at HHEX.
(c) *Demagnetisation process*. The regenerator material is cooled by the MCE and absorbs heat from the HTF, achieving to lower its temperature below the initial temperature of CHEX.
(d) *AMR heating process at constant magnetic field*. At zero field the HTF, cooled in process (c), is displaced from the regenerator towards the CHEX via fluid from the HHEX. The fluid in the CHEX absorbs heat from the medium to be cooled, which means the cooling capacity of the magnetic refrigerator. The temperature of the fluid in motion of the HHEX is higher than that of the magnetic material; therefore, the HTF yields heat to the magnetic material while moving towards CHEX. With this latter process, an AMR refrigerator working cycle is closed. As a result of the repetition of these processes in cycles the temperature span between the hot side and cold side of the AMR is increased. As the cycle is activated repeatedly, the temperature span becomes greater than the temperature range achieved by the MCE.

In Fig. 1, the lines of the graphs show, by way of example, the temperature profile in each stage of the cycle. The dashed line represents the initial profile in each process, and the solid line represents the end temperature profile in this process. Fig. 2 depicts the time diagram AMR cycle. The magnetisation and demagnetisation are simplified as linear variations in time of the applied magnetic field. It is optional whether to stop, or not, the fluid mass flow rate for a period (dwell time) during the magnetic field variations. In Fig. 2, it is assumed that the variation in the flow direction occurs when the maximum and minimum value of applied magnetic field is reached.

2.1. AMR refrigerator configuration

AMR refrigerators have evolved, in accordance with practical and theoretical limits, to the various fabrications which characterise the current prototyping scenary (see reviews by Gschneidner and Pecharsky in 2008 [13] and Yu et al. [14] in 2010).

AMR refrigerator prototypes can be classified into two basic categories based on the relative motion of the AMR with regard to the applied magnetic field: AMR refrigerators with reciprocating movement and AMR refrigerators with rotary movement. At the same time, within these categories, are different configurations depending on the type of magnetic source, the type of magnetocaloric

material, the design of AMR and the geometry of the magnetocaloric material.

The magnetic field can be generated either by using permanent magnets or by electromagnets. The latter can be subdivided into two categories of electromagnets: superconducting and non-superconducting electromagnets or traditional ones.

Most room temperature MR prototypes built to date have been built with permanent magnets. The first MR machine to use permanent magnets was developed by Zimm et al. [15]. The permanent magnet available with the highest product of maximum energy (BH_{max}) is made of a neodymium, iron and boron alloy called a NdFeB magnet. All of the sets of permanent magnets used in magnetic refrigerators use this type of magnet. Their arrangement may be in Halbach cells, concentrated or of a simple layout. A detailed analysis of the efficiency of different designs of permanent magnets used in magnetic refrigeration applications is presented in Refs. [16,17].

The magnetocaloric material used par excellence for the prototyping of AMR refrigerators is Gd lanthanide. Yet, there are prototypes constructed using Gd alloys with other materials, for example, Gd–Tb [18], Gd–Er, Gd–R [19], and $Gd_5Si_2Ge_2$ [20], and other magnetocaloric materials such as $La(Fe,Co)_{13-x}Si_x$ [21], for example. Numerous studies of magnetocaloric materials have been performed to find alternatives to Gd and are the main research field for room temperature MR. The series $La(Fe_{1-x}Co_x)_{11.9}Si_{1.1}$ may become the room temperature magnetocaloric materials of the future, due to their industrial scale manufacturing process, obtained through powder metallurgical processes that lower manufacturing costs [22]. More information about magnetocaloric materials can be found in Refs. [23–25]

As for the structural material engendered by the AMR magnetocaloric material, it is non magnetic, with the majority of the rectangular shaped AMRs being constructed with 304 or stainless steel 316, and the cylindrical shaped AMRs with plastic, acrylic or nylon tubing.

The geometry and arrangement of the magnetocaloric materials considered in the AMR are:

(a) tube channels in a solid block,
(b) a stack of perforated plates arranged perpendicular to the heat transfer fluid direction,
(c) a stack of solid plates arranged parallel to the heat transfer fluid direction, and
(d) a packed bed of spherical particles (loose packed or sintered).

The total porosity can vary between 40% and 60%. Various possible designs of regenerators and their efficiencies were considered by Barclay et al. [26,27]. Packed sphere regenerators have a significantly higher pressure drop than many other regenerator geometries, including parallel plate regenerators. The high pressure drop associated with packed sphere regenerators increases the necessary pump work and reduces the theoretical performance limit of the AMR technology. Parallel plates offer a potentially high-performance alternative to packed sphere regenerators, due to their relatively low pressure drop to heat transfer performance [28]

The HTF used in most of the room temperature AMR prototypes is natural, distilled or glycoled water. However, there also exists research and prototypes using gases (helium [29–31] and air [32]) and different oils [33,34]. The HTF is displaced in an oscillating manner by a rotary pump together with a system of valves or through a fluid displacer. The solution of a rotary pump and valve renders low vibration and reduced friction loss. It also enables a unidirectional flow according to where the valves are located in the hydraulic system outside AMR. However, it is more difficult to accurately control the amount of fluid displaced per cycle and ensure a constant use factor when the frequency is varied.

2.2. Considerations of design and construction of an AMR refrigerator

There are several difficulties associated with the design and construction of an AMR refrigerator. Scientists and researchers should know them and adopt measures to save or reduce them in order to minimise their influence in practice and thereby achieve temperature span and cooling power comparable to conventional systems based on vapour compression. Some of the considerations associated with the design and construction of an AMR refrigerator are:

- The efficiency of an AMR refrigerator, for a specified refrigerant, depends on good mechanical design, based on the AMR design, and the optimisation of operating parameters.
- The mechanical design of AMR systems is governed by the geometry of the field and by the type of magnetic source.
- In AMR refrigerators with permanent magnets, the field strength is limited and the leakage of magnetic flux must be prevented.
- The magnetic field should be as uniform as possible in the space occupied by the magnetocaloric material.
- The active mobile parts require high precision to avoid the reduction of magnetic field due to the air gap between the magnets and magnetocaloric material.
- The flow density should be as low as possible for a given temperature span and cooling power.
- The forces generated by the interaction between the magnetic field and the AMR should be minimised to reduce the force applied required for the relative movement.
- The AMR design must allow packing under the active work area for the greatest possible mass of magnetocaloric material with the maximum exchange area, and minimum pressure drops in the HTF.
- Changes in temperature are limited by the material used and multi-stage machines lose efficiency through heat transfer between stages. It is necessary to obtain refrigerant materials with larger MCE and with good cooling properties: low thermal and magnetic hysteresis, non-toxic, resistant to corrosion, low specific heat and high thermal conductivity and low manufacturing costs [35,36]. Resorting to regenerators of different alloys is also an option [37], but the optimal number of layers, the composition and geometry should be adapted to specific design conditions.
- The capacity to develop machines capable of operating at high frequencies: higher frequencies could mean greater cooling power. This calls for improvements in the geometry of the regenerator matrix to reduce the pressure drop while maintaining porosity and heat transfer with low axial conduction.
- The dead hydraulic volume between the regenerator and heat exchangers should be minimised.
- Implement control strategies that enable optimisation of the operating parameters without impairing efficiency.

Thus, in order for room temperature magnetic refrigeration to become a feasible alternative to conventional cooling technology, the aforementioned items must be considered in designing refrigerators.

3. Comparison of the configuration of magnetic refrigerators

The rotary AMR refrigerator enables a continuous cooling compared to the typical reciprocating movement configuration with a single regenerator, as in this case refrigeration is only produced during one stage of the AMR cycle. To achieve continuous cooling

with reciprocating AMR machines it is necessary to resort to double AMR constructions and a system of valves and piping which allow the synchronisation of the HTF flow with the application of the magnetic field.

Reciprocating systems are reliable and relatively easy to implement, but can be bulky and have large inertial forces that limit both the frequency of operation as well as mechanical efficiency. The working frequencies of reported reciprocating prototypes vary between 0.2 and 1 Hz.

In rotary machines, inertia forces do not have as much impact, since the rotation movement is inherently more balanced and stable. Because of this, they allow higher operating frequencies with a smaller AMR and compact magnet systems. This all means less relative displacement work between the magnets and AMR, rendering them possibly more efficient. However, from a practical approach, they can be more complex in terms of sealing and leakage.

Various rotary prototypes that have reached an operating frequency of 4 Hz [38,39] and even 8 Hz [40] and 10 Hz [41]

AMR refrigerators with fields generated by means of an electromagnet often require little or no mechanical movement frequency. However, the magnetic fields generated through non-superconducting electromagnets require large power sources and cooling systems to avoid overheating of the coils. The superconducting electromagnet is a better option than the traditional electromagnet, as it requires little energy to operate once the electromagnet has become superconductive and its ohmic resistance can be considered negligible. Superconducting magnets can reach magnetic flux densities much higher than conventional ones. The drawback is that they require a complex and costly for the continuous cooling of the superconductor. However, for large scale applications, such as large refrigerators for warehouses, etc., a superconducting electromagnet could be a viable solution. For domestic systems, AMR refrigerators with permanent magnets offer advantages over superconducting magnets and conventional electromagnets. Hence the permanent magnets do not require energy to generate a magnetic field, do not require auxiliary equipment and can be geometrically small, enabling a compact refrigerator design.

3.1. Rotary MR systems

The rotary AMR consists of a wheel with multiple regenerators. In its operating mode, through a relative movement of rotation between magnets and AMR, a regenerator enters the magnetic field and rejects the heat while another regenerator is removed from the magnetic field and absorbs heat.

Among the different configurations, one of the most significant and recent is that developed by Engelbrecht et al. [40] of rotary AMR using concentric Halbach cylinder magnets with a continuous flow of HTF provided by a pump and a rotary distribution system. Fig. 3 shows a photo of the prototype. The researchers reported the following results: operating frequencies of up to 8 Hz, cooling capacities of around 1 kW operating with a span near 0 K, a maximum temperature span of 25.4 K with no load, 100 W cooling power with a 20.5 K span and a COP of 1.8 for a 400 W and 8.9 K span. The AMR refrigerator has 24 Gd regenerators with a total mass of 2.8 kg, occupying a volume of 0.57 dm^3.

Another interesting system is the prototype presented by Tura and Rowe in 2011 [42], based on a rotating magnetic system (does not require dynamic sealing) and a displacer for HTF flow. Using 110 g of Gd as a coolant, the device produces a maximum span of 29 K with no thermal load, and 10 K under a cooling load of 50 W. The maximum operating frequency was limited to 4 Hz due to the large pressure drop in the regenerators.

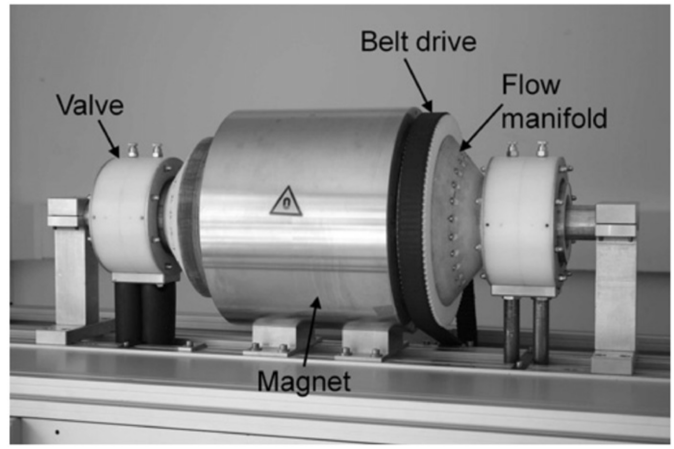

Fig. 3. Photograph of rotary AMR refrigerator designed by Engelbrecht et al. [40], with permission of the author.

Russek et al. [43] built a rotary AMR refrigerator with a fixed regenerator and rotating permanent magnet. The researchers reported 844 W with a span close to 0 K and 400 W in an 8.1 K temperature range. The AMR contains 890 g of Gd and the maximum operating frequency is 4.7 Hz.

In 2007, Zimm et al. [44] presented a prototype formed by a rotating magnetic structure (providing a maximum magnetic field of 1.5 T) and 12 fixed regenerators, where the porosity of each regenerator is 52%, with a total mass of 916 g of Gd. The system reaches a maximum cooling power of 220 W and a maximum temperature range of 11 K. The maximum operating frequency established was 4 Hz.

Various rotary AMR devices have been constructed and reported for implementing at room temperature. This section has only made reference to some more of the latest ones highlighting some features since it is out of the scope of the paper. For more information see Ref. [14]

3.2. Alternative MR systems

The first room temperature MR system developed was based on a reciprocating Ericsson cycle, and was built by Brown in 1976 [7]. The machine reached a temperature difference of 46 K between the cold and hot sources, using 158 g of Gd in a 7 T magnetic field created by helium cooled superconductors. For the HTF, a mixture of water and 20% ethyl alcohol was used. Another alternative machine that marked the development of modern magnetic cooling technology was built by Zimm et al. [45]. This device reached a 600 W of cooling power with a temperature span of 10 K working with a 5 T magnetic field with superconducting magnets.

This section gives a detailed review of some of the latest alternative MR systems, providing design concepts and operating characteristics. Such characteristics concern operating frequency, magnet type and field strength, regenerator materials and geometry, and maximum temperature span and cooling capacity.

3.2.1. Gao et al. magnetic refrigerator

In 2006, Gao et al. [20], at the Xi'an Jiaotong University in China, built an experimental room temperature magnetic refrigerator. The working mode is based on the AMR cycle. The conceptual scheme of the experimental AMR system is shown in Fig. 4. The refrigerator design does not allow continuous refrigeration. The AMR moves within the magnetic field with a linear reciprocating movement, thanks to a step motor and ball screw. The magnetic field is created by water-cooled electromagnets, reaching 2.18 T in a 60 mm air gap.

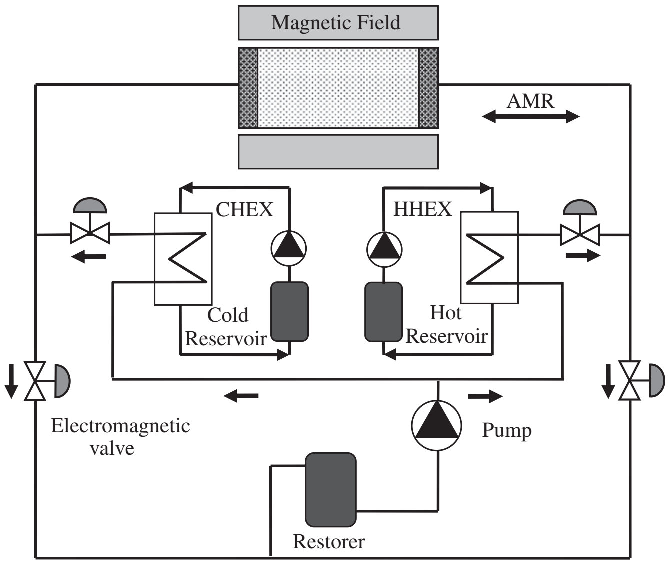

Fig. 4. Schematic of AMR experimental system [20].

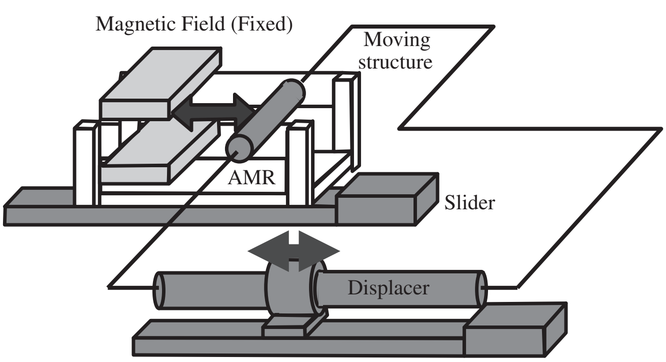

Fig. 5. Schematic of experimental apparatus Nakamura et al. [32].

The AMR was constructed from stainless steel of rectangular shapes measuring $140 \times 76 \times 36$ mm^3. The heat transfer circuit comprises; HHEX, CHEX, a circulation pump and four valves. This circuit is responsible, by the appropriate activation of the valves, for pumping water as HTF through the AMR during the intervals of reciprocating movement of the AMR. Three types of magnetic refrigerant (type I: 930 g of gadolinium particles with an average diameter of 0.3 mm; type II: 1109 g of gadolinium particles with an average diameter of 0.55 mm and type III: 1213 g of $Gd_5Si_2Ge_2$ alloy particles from 0.3 to 0.75 mm) are packed in the AMR. To retain the particles, stainless steel mesh number 700 was used. Investigations were carried out to determine the magnetic refrigerator performance under various temperature ranges, flow and flow conditions. The time per circulation cycle fraction of the HTF through the considered regenerator is between 2 and 6 s, with flow rates varying from 0.02 to 0.06 L/s. The results indicated a maximum cooling power of 18.7 W, 17.8 W and 10.3 W for types I, II and III respectively, under a temperature span of 3 K. The cooling power was also reduced by the increase in particle size.

3.2.2. *Nakamura et al. magnetic refrigerator*

At the University of Hokkaido in Japan, Nakamura et al. [32] built an experimental refrigerator based on the AMR cycle. Shown in Fig. 5 is the schematic of the experimental device. As with the preceding prototype discussed, the refrigerator does not allow continuous refrigeration. The AMR was constructed from 20 mm diameter acrylic tubing, containing 33.4 g of Gd spherical particles. The fraction of volume held by the magnetocaloric material is 62.6% and the active length of the regenerator was 60 mm. The magnetic field was created by two static NdFeB permanent magnetic sources that produce around 2 T in the middle of the air gap. The AMR moves within the magnetic field with a linear reciprocating movement, owing to a slider. Scientists identified the temperature profiles under various operating conditions for the AMR working with water and air as HTF. With water a greater span than the adiabatic temperature change (4.2 K) was reached after 1000 s, and with air after 500 cycles, when the initial temperature was 293 K for both trials. Furthermore, the authors reflected the necessity of a larger volume of air displaced in comparison with water, to achieve optimum operating conditions.

3.2.3. *Hirano et al. magnetic refrigerator*

Hirano et al. [46] built a prototype similar to the experimental refrigerator constructed earlier by Nakamura et al. [32]. The researchers modified the Halbach type magnetic circuit to achieve a 2.3 T maximum magnetic field. The total weight of the magnetic structure was 83 kg, with dimensions of 240 mm in width, a height of 186 mm and 160 mm in depth. The AMR was also fitted in a tube with an external diameter of 20 mm, an active length of 60 mm and an inner diameter of 12 mm. The magnetocaloric material used consists of different types of LaFeSi alloy spherical particles. The HTF used was air, moved with a compressor. The results obtained showed a span (2 K), lower than that observed with Gd.

3.2.4. *Zheng et al. magnetic refrigerator*

This magnetic refrigerator developed by Zheng et al. [47] at the Technological University of South China is of a reciprocating type, consistent with the AMR cycle and based on the Ericsson cycle for continuous cooling. Fig. 6 shows the developed AMR system configuration. The system runs close to room temperature, in a magnetic field created by an NdFeB permanent magnet according to the structure in Fig. 7(a). With the application of a finite element method, scientists predicted a maximum magnetic field intensity of 1.5 T in

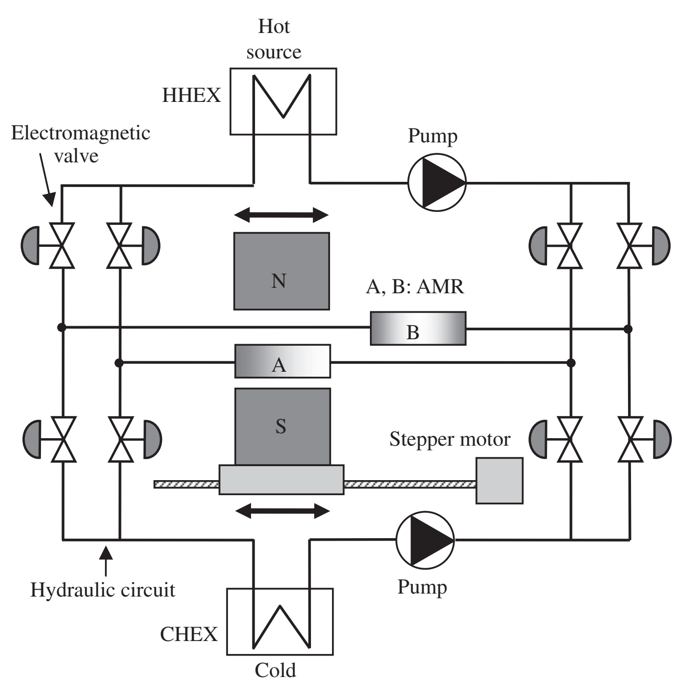

Fig. 6. AMR system developed by Zheng et al. [47].

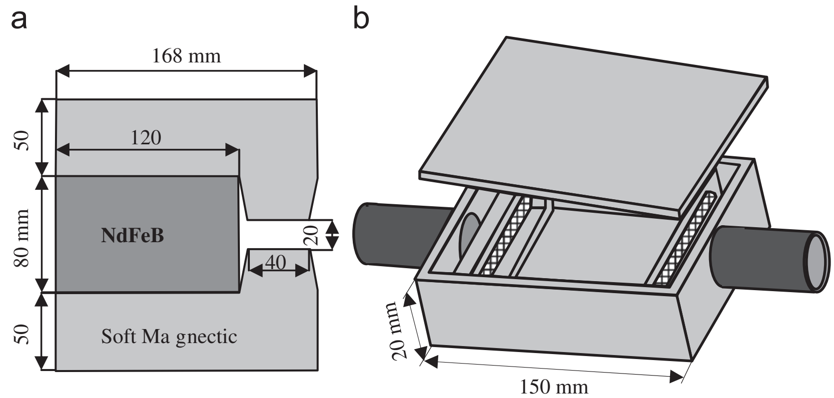

Fig. 7. (a) Schematic of the magnetic structure and (b) schematic of AMR structure [47].

the central area of the air gap. The refrigerator comprises double AMR made of stainless steel 304, each rectangular in shape and measuring $150 \times 40 \times 20\ mm^3$ (see Fig. 7(b)). Between each AMR is a distance of 80 mm. The magnetocaloric working material used is particles of gadolinium held by stainless steel screens with a mesh number of 200. The refrigerator comprises, besides the double AMR, two heat exchangers (CHEX and HHEX), two unidirectional flow pumps and control subsystems. The double AMR is magnetised and demagnetised cyclically by the reciprocating movement of the permanent magnet at a speed of 0.02 m/s. The mechanical system of magnet movement consists of a step motor and ball screw. To meet the thermal requirements of the cycle, the flow of HTF is synchronised with the magnetisation/demagnetisation by the arrangement and coordination of eight valves. The magnet stops moving in the magnetisation process for 2 s, long enough to ensure the exchange of heat when an AMR is completely inside the magnetic field. Water is used as the HTF. The experimental results of the prototype in terms of performance and cooling capacity were not presented.

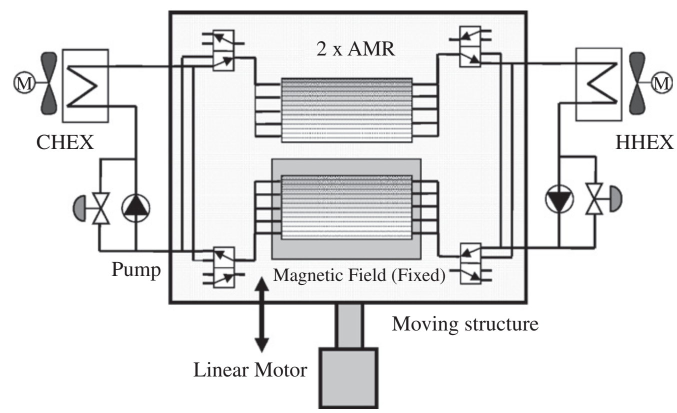

Fig. 8. Outline of the AMR demonstration unit developed by Tagliafico et al. [48].

3.2.5. *Tagliafico et al. magnetic refrigerator*

At the Genoa University, Tagliafico et al. [48] announced the design and construction of a linear reciprocating magnetic refrigerator for use as a demonstration unit.

The unit is based on the AMR cycle, performed by two AMRs arranged in parallel and a field created by permanent magnets. It also comprises CHEX and HHEX equipped with an air fan in order to increase heat transfer by convection between the HTF and the environment, two variable-flow pumps, a hydraulic distribution system made up of four two-position three-way valves, and a linear motion system. Fig. 8 shows the outline of the prototype.

The active magnetocaloric material is Gd and the HTF is water with corrosion inhibitors. The magnetic structure shown in Fig. 9, comprising ten NdFeB magnets (5 kg in weight) and the Fe alloy magnetic core ensures a uniform magnetic field density of 1.55 T, measured in air. The total weight of the structure is 30 kg. The air gap for the AMR is 13 mm in thickness, 10 cm in width and 50 mm in length. The two regenerators are composed of five parallel carbon pipes each, plus three other dummy pipes filled with gadolinium: one of them between the regenerators to guarantee the required spacing (for residual field minimisation on the demagnetised bed), and the other two at the ends of the pipe series to balance the magnetic forces. The overall dimensions of the regenerator are $50\ mm \times 9.5\ mm \times 100\ mm^3$. Gd was arranged in particles with an average size of 0.3 mm, with a total weight of 400 g. The void fraction of the AMRs is of 0.46. The movement of the regenerators is achieved with a linear motor using a rigid structure (shuttle). The offset distance/displacement distance is 70 mm in a time of 0.2 s. The shuttle includes distribution channels for the distribution of fluid to the AMRs.

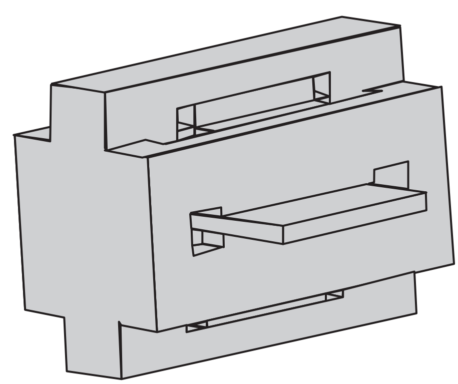

Fig. 9. Geometry of the Halbach magnet of Tagliafico et al. [48].

Software synchronises the movement of the AMRs and the valve operation, in order to obtain the desired fluid flow rate in relation to the magnetic field application time. The time sequence can be varied to optimise the process.

3.2.6. *Engelbrecht et al. magnetic refrigerator*

In Denmark, Engelbrecht et al. [49] devised a simple reciprocating magnetic refrigerator within a cylindrical tube, which does not allow continuous cooling. The objective of the prototype was to compare the performance with different candidate magnetocaloric materials for AMRs and different AMR designs. Fig. 10 outlines the operating principle and the design of the AMR housing. The researchers assessed the performance of three magnetocaloric materials: $La(Fe,Co, Si)_{13}$, $(La,Ca,Sr)MnO_3$ and Gd in an AMR with

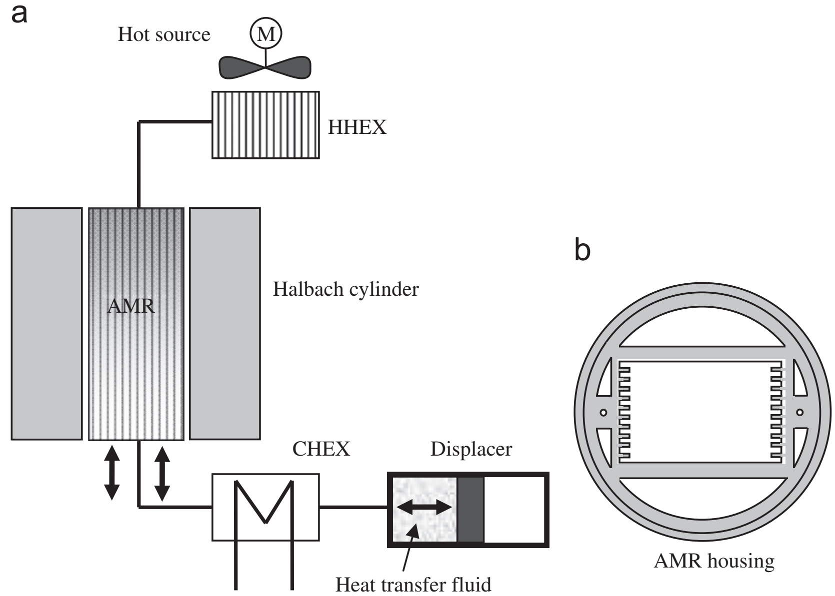

Fig. 10. (a) Schematic of AMR experimental system and (b) AMR housing [49].

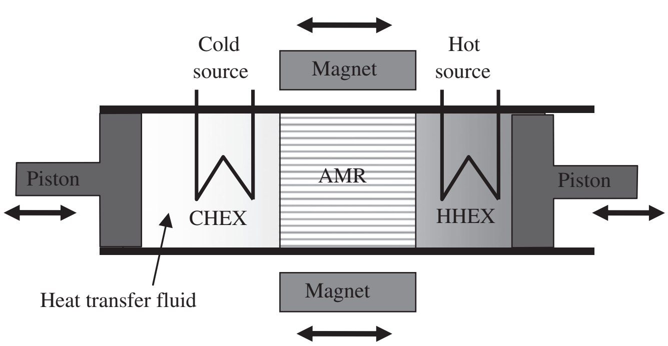

Fig. 11. Diagram of the prototype developed by Petersen et al. [51].

material arrangement in the form of parallel plates with a separation between them of 0.5 mm. The magnetic field was created by permanent magnets forming a cylindrical Halbach cell, reaching a flow density of 1.03 T. Magnetisation and demagnetisation of the regenerator is accomplished by moving the regenerator vertically in relation to the stationary magnet by means of a step motor and ball screw. A mixture of 75% water and 25% antifreeze was used as the HTF. Ethylene glycol antifreeze acts as a corrosion inhibitor reducing corrosion of the magnetocaloric material. The magnetic refrigerator's working parameters are the HTF displacer stroke, the HTF speed and the speed with which the AMR is introduced into the magnetic field. The researchers reported a higher temperature span than was achieved with the Gd AMR, reaching 10.2 K with a room temperature of 297 K. The working conditions were with a cycle of 8 s and a fluid speed of 8.22 mm/s.

The design of this prototype is similar to that previously built in the Risø DTU laboratory [50] and to that constructed by Petersen et al. [51]. Fig. 11 shows a simplified diagram of the prototype developed by Petersen et al. [51]. The ring-shaped magnet (Halbach type) reaches 1.2 T. The magnetocaloric material used was Gd in the form of parallel plates 5 cm in length and 1 mm thick. It achieved a span of nearly 9 K.

3.2.7. *Trevizoli et al. magnetic refrigerator*

In 2010 at the IV International Conference on Magnetic Refrigeration at Room Temperature [52] and subsequently in 2011, Trevizoli et al. [53] described the design, workings and preliminary results of an experimental magnetic refrigerator. The machine was designed with a single static AMR. Fig. 12 schematically illustrates the pilot refrigerator's equipment. Its mode of operation does not allow continuous refrigeration in the cold source. The working fluid is water pumped with a reciprocating pump. The magnetic source is a Halbach cell with NdFeB magnets, reaching a maximum magnetic field of 1.65 T, in a 10 mm air gap. The linear reciprocating movement of the Halbach cell for the executions of magnetisation and demagnetisation of AMR is through a pneumatic system. The Halbach cell dimensions are 126 mm length, 131 mm width and 191 mm height with a rectangular geometry. The AMR housing is stainless steel 304 and Gd is the magnetocaloric material arranged in 28 parallel plates (160 mm in length, a thickness of 0.85 mm, and 6.4 mm in height) spaced at 0.1 mm. The fraction of regenerator volume occupied by water is 9.2%. The total mass of Gd in the regenerator is 195.4 g., 154.4 g of which are useful due to the concentration of the magnetic field in the 126 of the 160 mm held by the AMR. The researchers tested the refrigerator with and without thermal load, under a working frequency of 0.14 Hz. Each of the four processes of the Brayton cycle is completed in 1.75 s. Preliminary results presented by Trevizoli et al. [53] displayed a difference in temperature of 4.4 K between the hot and cold source with a room temperature from the hot source of 296.15 K. The maximum cooling capacity achieved was 3.9 W, also for a room temperature from the hot source of 296.15 K. The researchers reported no information about the COP obtained by the prototype.

3.2.8. *Balli et al. magnetic refrigerator*

Balli et al. [33] presented a prototype as a magnetic refrigeration system at room temperature for its pre-industrial application (Fig. 13). The magnetic refrigerator design was made to reduce power consumption and increase the thermodynamic performance of the system. For this, one of the objectives was to reduce applied displacement forces by means of the compensation of magnetic forces. The researchers claim that this was achieved thanks the design of the AMR. The prototype consists of two static NdFeB permanent magnet sources producing about 1.45 T in an air gap of 12 mm, two regenerators with Gd plates and four heat exchangers. Each regenerator is divided into two parts separated by a distance of 30 mm, containing 200 g of Gd in parallel flat plates of 1 mm in thickness,

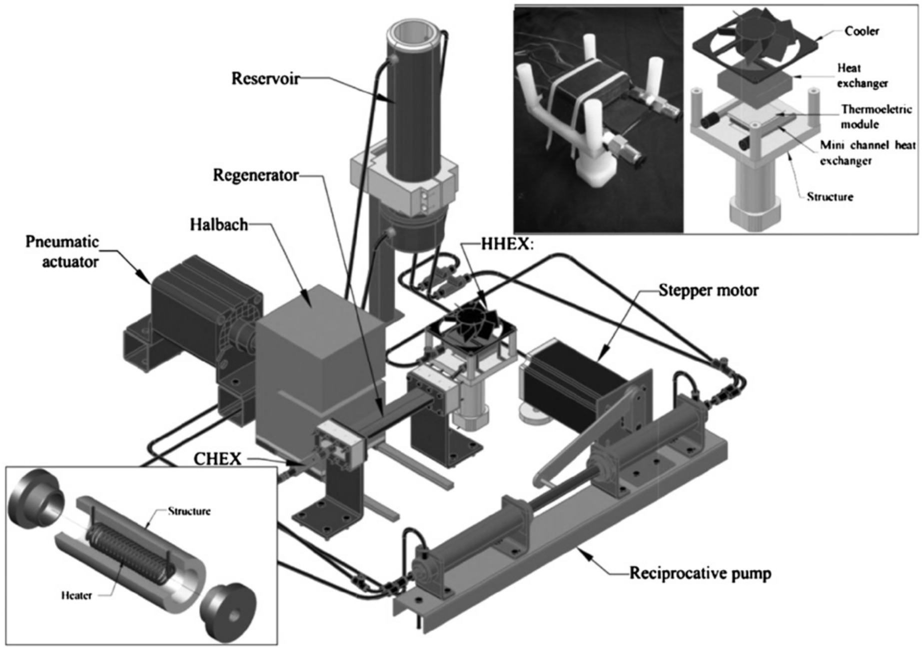

Fig. 12. AMR test apparatus Trevizoli et al. [53], with permission of the author.

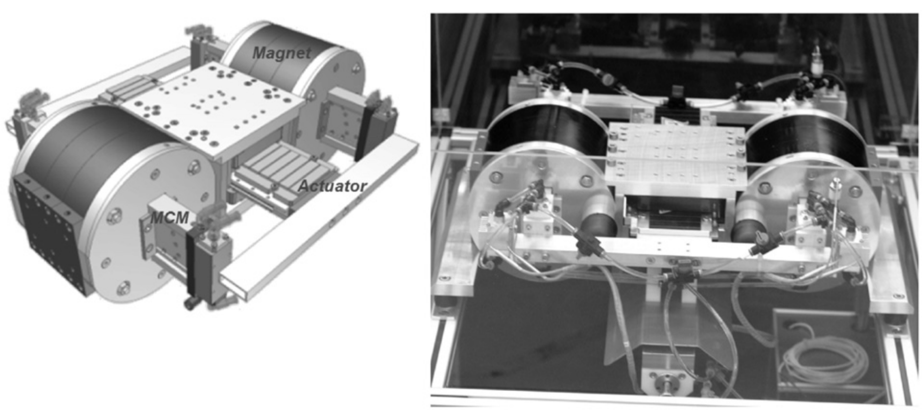

Fig. 13. Reciprocating AMR refrigerator designed by Balli et al. [33], with permission of the author.

8 mm wide and 100 mm in length with an AMR porosity of 0.16. The total mass of the machine's magnetocaloric material is 800 g. Water, silicone oil and zitrec were tried as the HTF. The diagram of the AMR cycle and the design of the regenerator are shown in Fig. 14. The configuration of the AMR into two parts allows the compensation of forces. When one part of the regenerator is displaced and magnetised, the other part is automatically demagnetised, allowing the reduction of applied force for the displacement of the AMRs.

The cooling power of the magnetic refrigerator reported by investigators is between 80 and 100 W with a greater temperature span of 20 K, using water as the HTF, with a mass flow rate of 20 g/s and with a working frequency of 0.5 Hz. However, data about the COP of the machine was not disclosed.

4. Authors' research on MR

A prototype of a reciprocating AMR refrigerator at room temperature designed by the authors themselves is under construction and investigation of the authors.

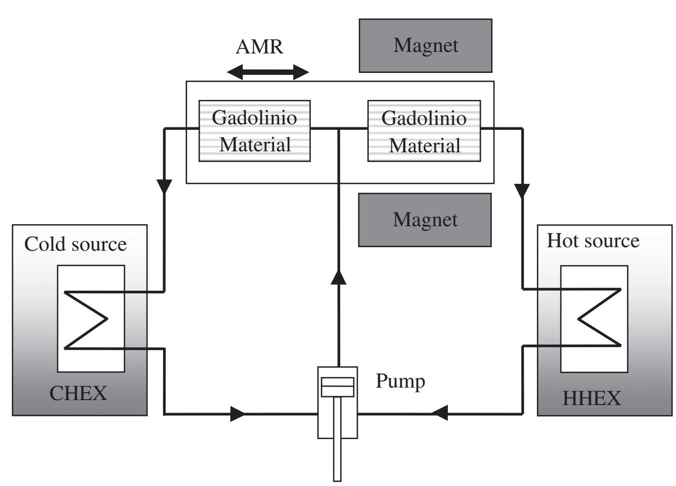

Fig. 14. Schematic of the AMR cycle and design of the regenerator implemented by Balli et al. [33].

In the linear magnetic refrigeration machines working with the AMR cycle, the magnetisation-demagnetisation process requires a large mechanical energy to move the active material in and out of the magnetic field. This is a consequence of the forces generated by the interaction between the magnetic field and the magnetocaloric refrigerant as well as by the inertial forces inherent to the reciprocating movement and the frictional forces. On the other hand, the COP of an AMR refrigerator is given by

$$COP = \frac{Q_c}{W_{total}} \tag{1}$$

where Q_c is the heat extracted from the cold source reservoir and W_{total} represents the total work required to do so.

The total work supplied to the refrigerator can be defined as the sum of two terms

$$W_{total} = W_{mag} + W_{heat\text{-}pump} \tag{2}$$

where W_{mag} is the work absorbed by a device to move the active material in and out of the magnetic field and W_{heat_pump} is the work required by the heat transfer loop. Depending on the design of the AMR refrigerator, $W_{heat\text{-}pump}$ is the sum of the pump work of the HTF, the work required to operate the fluid distribution valves and the work of the CHEX and HHEX air fan. W_{mag} constitutes a large proportion of total energy absorbed by the machine. It can be expressed as follows:

$$W_{mag} = \frac{\int \vec{F} \times \vec{dl}}{\eta_{d.sys}} \tag{3}$$

where $\vec{F}$ is the force applied by the displacement system, $\vec{dl}$ represents the displacement of the AMR and $\eta_{d.sys}$ the efficiency of the displacement system. According to Eqs. (1)–(3), the reduction of $\vec{F}$ is important to achieve more efficient AMR refrigerators. With the aim of reducing the applied force, and thereby the electrical power required for the reciprocating movement of the AMR, and contribute to increasing the COP of the refrigeration machine, the authors have devised a machine with a force restitution with passive magnetic fields and a double AMR.

The combination of the force restitution system with the double AMR design allows the reduction of displacement forces and compensation of the inertial forces. The inertial forces in reciprocating machines may require high energy peaks. The patent for the machine was applied for in Spain on 3rd April 2012, coded with the application number P201230512.

4.1. Experimental AMR refrigerator

The experimental prototype designed comprises a stationary permanent magnet structure that guarantees a uniform magnetic field in the centre of the 6 mm air gap. The AMR consists of two parallel regenerators, with a separation of 15 mm that permits a double AMR cycle to be carried out. The housing of the AMR is of stainless steel 316, with Gd as the magnetocaloric material. Each regenerator features 15 parallel plates (40 mm in length 40 mm wide and 0.5 mm high) separated by 0.25 mm. The total mass of magnetocaloric material is 180 g. The fraction of volume taken up by the Gd is approximately 60%. The overall dimensions of the AMR are: 245 mm × 130 mm × 4.5 mm. A simple heat transfer circuit formed by a CHEX, a HHEX, a circulation pump and two three-way two-position valves, is responsible for fulfilling the thermal demands of the working cycles. Fig. 15 shows a photograph of the magnetic structure and the double AMR with a displacement reciprocating force restoring system using passive magnetic fields.

Shown in Fig. 16 is the schematic of the implemented AMR cycle, demonstrating its main components. The working principle is as follows: during the first semi-cycle of operation one of the regenerators (2) is subjected to the magnetic field action generated by the

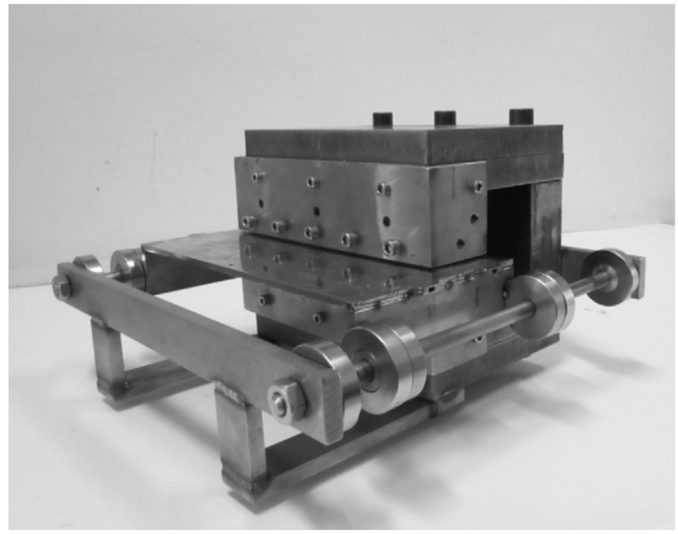

Fig. 15. Layout of the proposed prototype composed of a double AMR and a displacement force restoring mechanism implemented with passive magnetic fields.

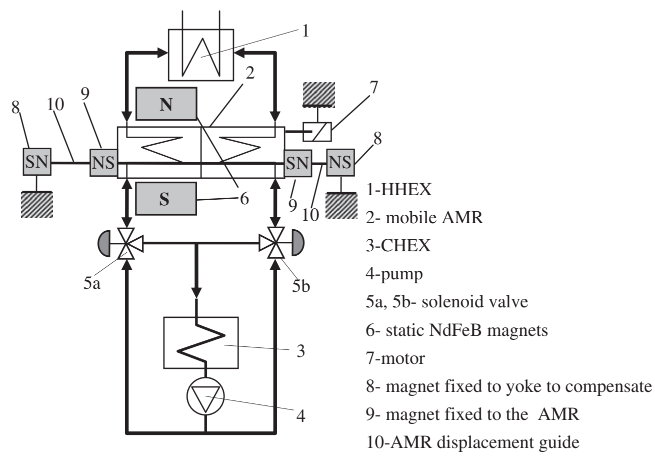

Fig. 16. Schematic of the AMR cycle implemented by the authors.

permanent magnets (6). As a consequence of this field, the material contained in this part of the regenerator undergoes the MCE. The HTF, consisting of glycol water, is pumped via the circulation pump (4) through the servo-valve (5a) activated during the first semi-cycle to absorb the heat generated by the magnetocaloric material whilst it is cooled. The heat absorbed from the magnetocaloric material is ceded to the environment in the HHEX (1). Once the heat is ceded, the HTF is returned through the other regenerator. Upon contact with the magnetocaloric material, whose temperature has decreased as a result of being removed in the previous semi-cycle from the presence of the magnetic field, the HTF is cooled. The cooled HTF passes through the two-position three-way valve (5b) toward the CHEX (3). Once the first semi-cycle is finished, the valve positions change simultaneously (5a) and (5b) whilst the AMR moves (2) within the magnetic field, thus inverting the flow direction of the circulating HTF. In this way the working cycle is completed, a process which is repeated during the entire running time of the machine. The authors do not yet have the final results because the prototype is undergoing testing.

5. Conclusions

This paper has conducted an exhaustive review of the technological advances associated with alternative AMRs of recent years,

providing a description of the working mode of both reciprocating and rotary prototypes and highlighting their advantages and disadvantages. Alternative types are reliable and relatively easy to implement, but can be bulky and are subject to large inertial forces that limit both the frequency of operation and mechanical efficiency. The rotary types allow higher operating frequencies due to the inherently more balanced and stable movement. They require, however, more complex AMR designs and may deliver problems in terms of sealing and waterproofing. To date, the maximum cooling capacity achieved by an AMR refrigerator is of 1 kW with rotary configuration. From the review carried out of alternative prototypes, it is concluded that alternative machines must have longer AMRs in order to obtain a larger temperature range. This is due to their low working frequencies compared to those of rotary. The potential improvement requires the implementation of designs and systems that enable the reduction of displacement forces.

The combination of solid-state refrigerants, water based HTF and high-efficiency machines are features that place MR as an environmentally safe refrigeration technology with zero ozone depletion potential, zero global warming potential and no greenhouse effect.

Commercialisation of refrigerators depends on the ability to meet performance objectives as well as acceptable costs of the device, not to mention the necessary breakthrough in the field of magnetocaloric materials' science.

To investigate alternative AMR refrigerators, the authors are conducting preliminary tests on a prototype based on a design to reduce the displacement forces.

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